

# ZTF Variable Science

## Recent Activity



ZTF

Tom Prince (Caltech)

Eric Bellm (UW)

**Kevin Burdge** (Caltech)

**Michael Coughlin** (Caltech)

Lynne Hillenbrand (Caltech)

David Kaplan (UWM)

Cow-Cheung Ngeow (NCU)

[Monika Soraisam (NOAO)]

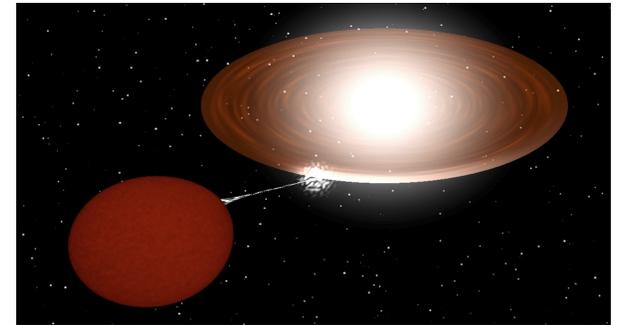
Paula Szkody (UW)

**Thomas Kupfer** (KITP-UCSB)

Jan van Roestel (Nijmegen)

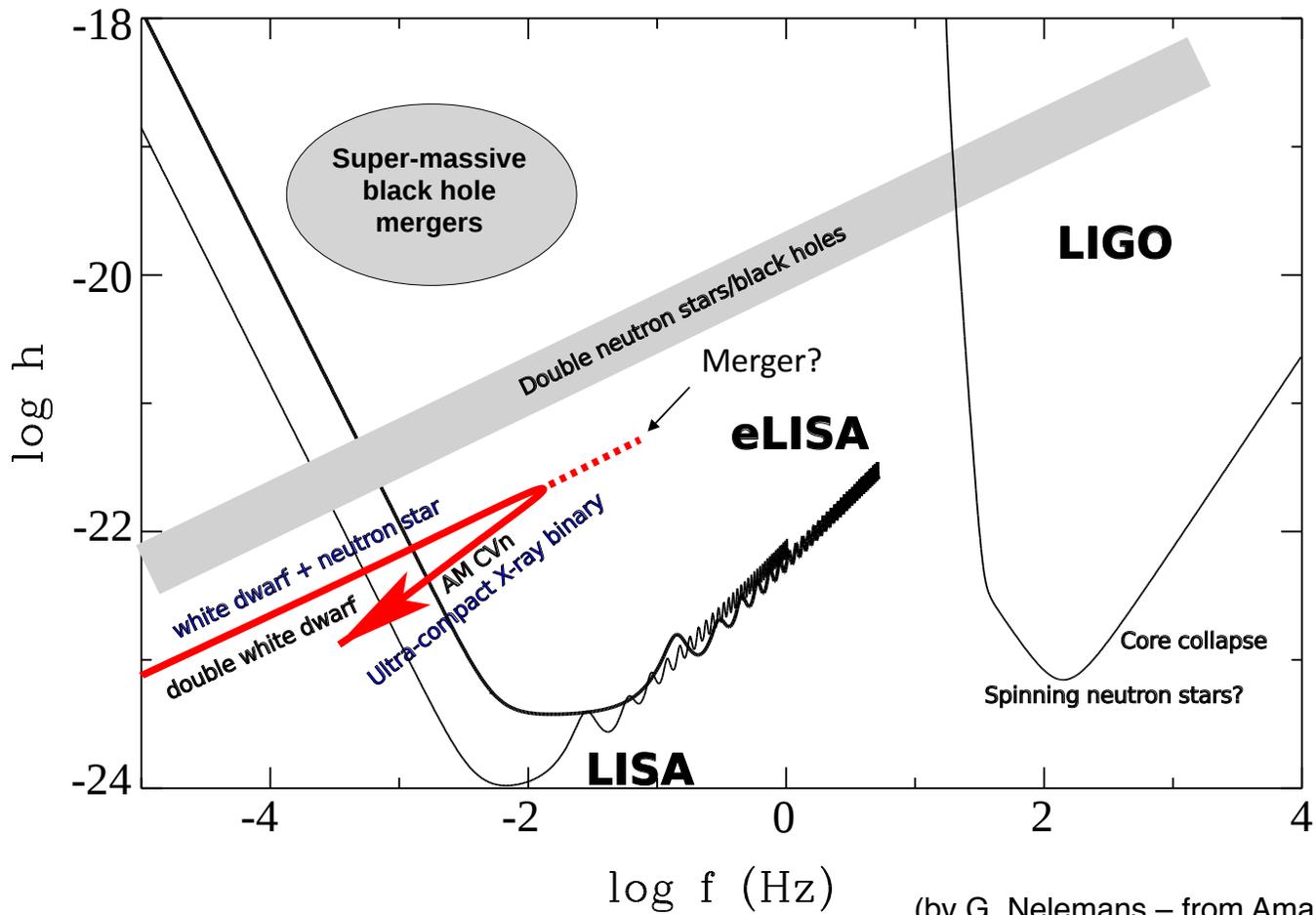
# This Talk

- Ultra-compact binaries ( $P \leq 70$  min)
  - Results of common envelope evolution
  - Progenitors of merger products (e.g. SN Ia)
  - White Dwarf (WD) structure and atmospheres
  - Gravitational Wave sources
  - *New results!*
- Other stellar/variability topics
  - Cataclysmic variables (CVs)
  - M31/M33
    - Plans for upcoming observations
  - Fermi Unidentified Sources (see David Kaplan)



# Important Trends

- **Gaia + PanSTARRS + ZTF** offer dramatic new opportunities
  - Gaia
    - Distances via astrometry (parallax and proper motion)
    - Construct HR diagrams: enables source selection
  - PanSTARRS
    - Colors (often better than Gaia)
  - ZTF
    - Dense time sampling of galactic plane and limited areas of high latitudes
- **LISA** – *the next frontier of gravitational wave astronomy*
  - Ultra-compact binaries
  - Massive BH mergers
  - Extreme mass ratio inspirals (EMRIs)



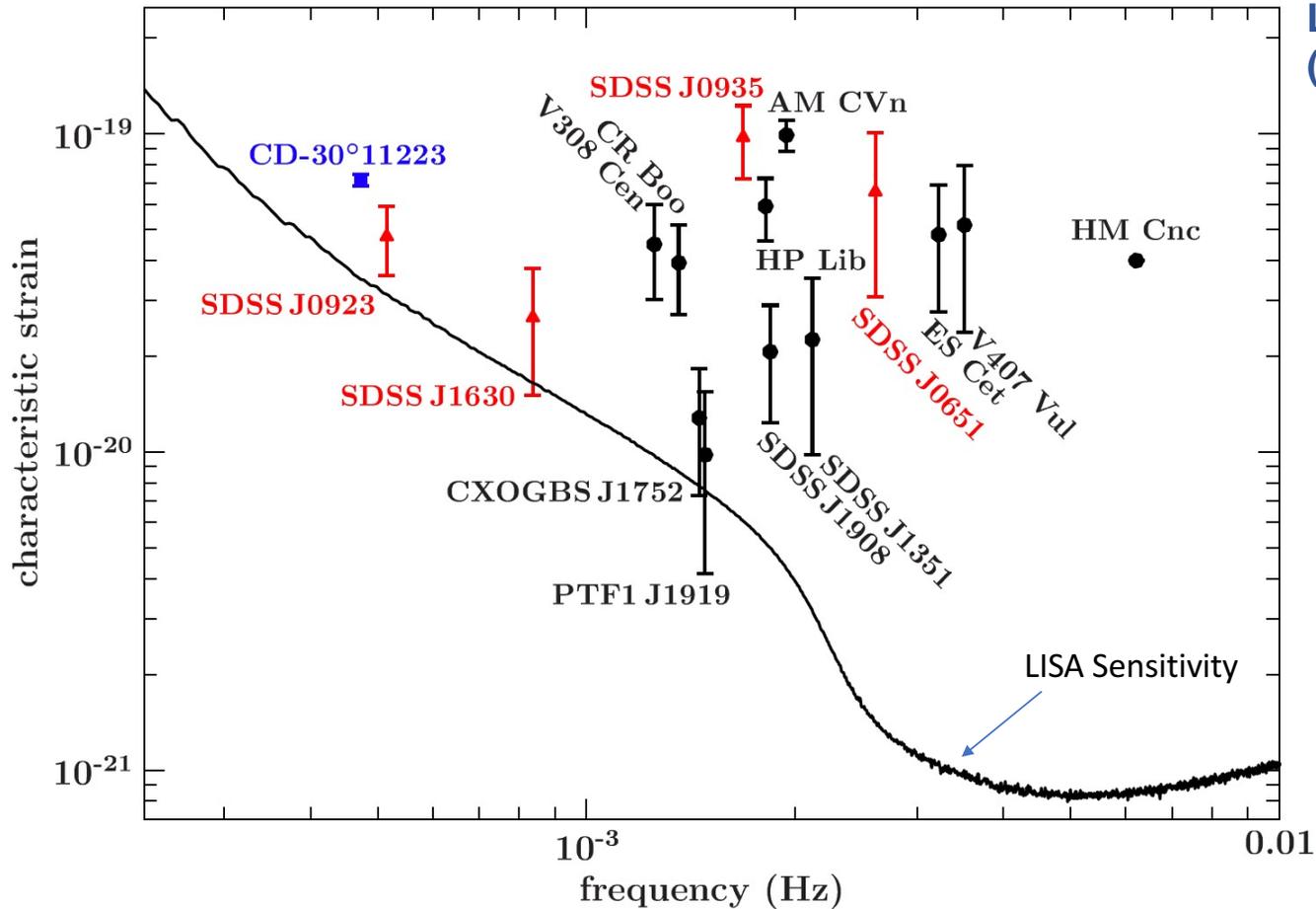
**Big Picture:  
Gravitational  
Waves &  
Compact  
Binaries**

(by G. Nelemans – from Amaro-Seoane+12)

## LISA Verification Binaries (Optical/X-ray Identifications)

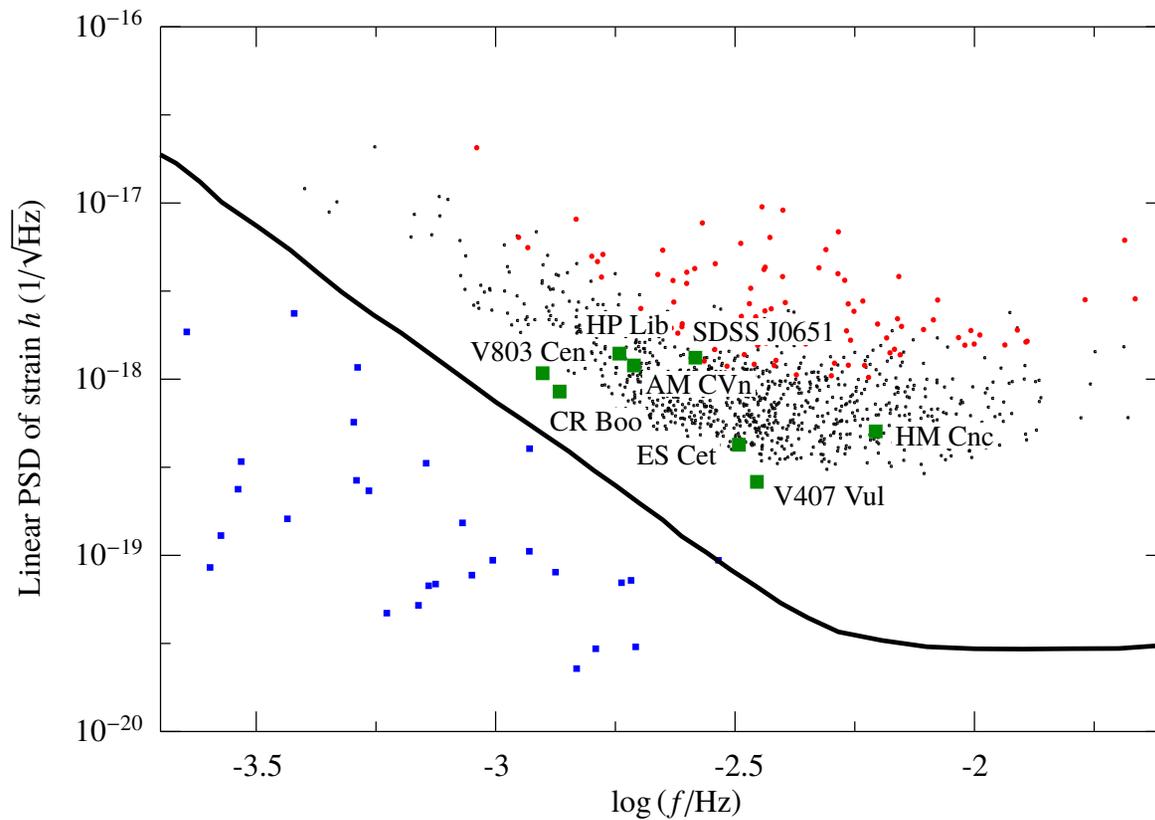
(From Kupfer+18, MNRAS  
using new Gaia data)

**Black circles** are AM  
CVn systems, **red  
triangles** correspond to  
detached white dwarfs  
and the **blue square** is  
the hot subdwarf binary.



*All discovered either spectroscopically, via outbursts, or in X-rays. PTF/ZTF discovery through periodicity detection in the time domain*

# Brightest LISA Ultra-compact Binaries

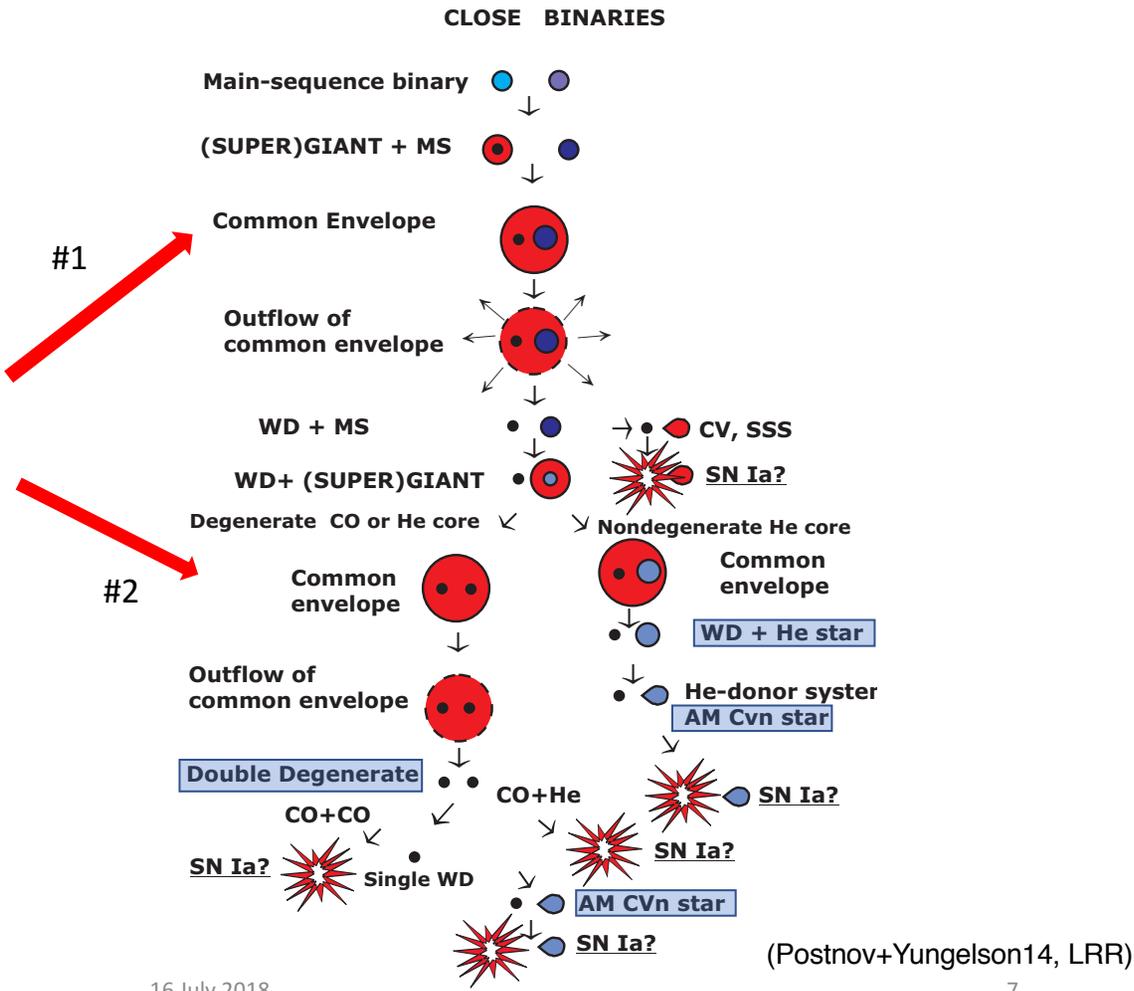


Green: LISA verification binaries  
Red: 100 strongest LISA sources  
Black: 1000 strongest LISA sources  
Blue: Other known binaries

(Simulation from Amaro-Seoane+12)

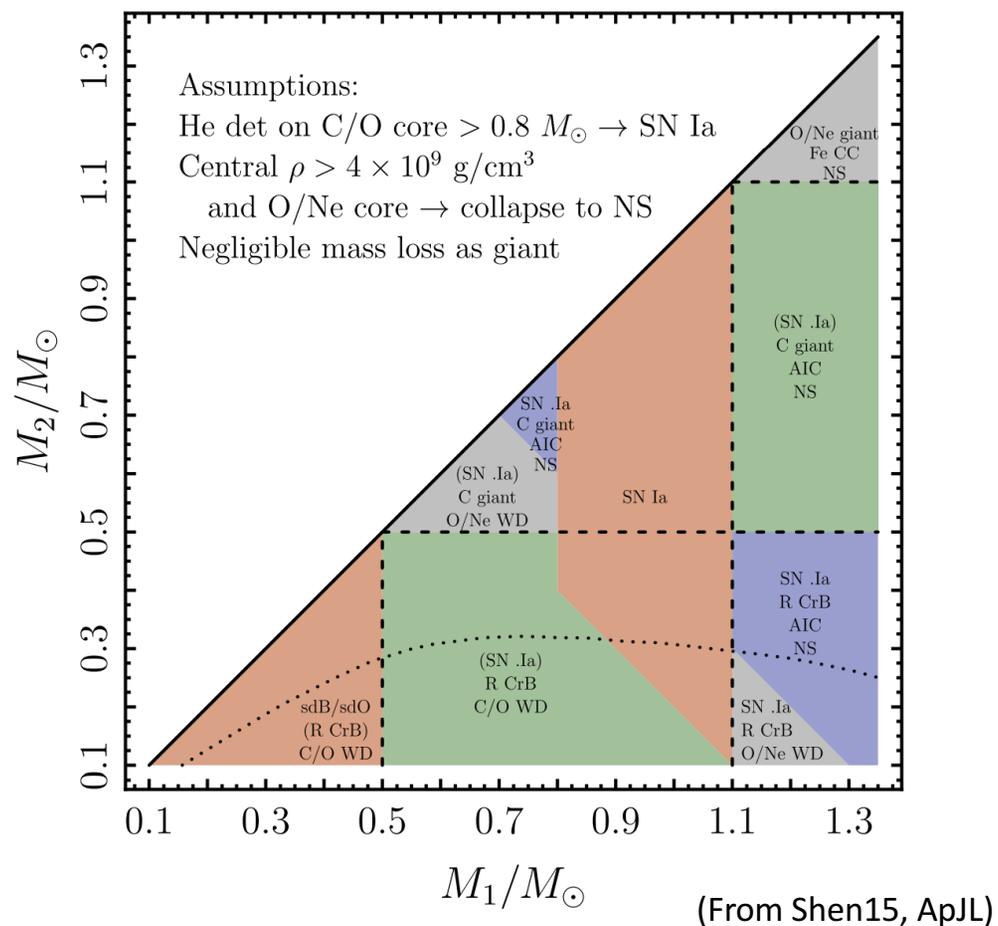
# Evolution of close binaries

- Ultra-compact binaries typically require two episodes of common envelope evolution
- Result in a variety of possible ultra-compact binaries
  - WD + He star
  - Double degenerate WD (DDWD)
  - AM CVn mass-transfer system



# Complexity of End States of Double Degenerate WD Merger

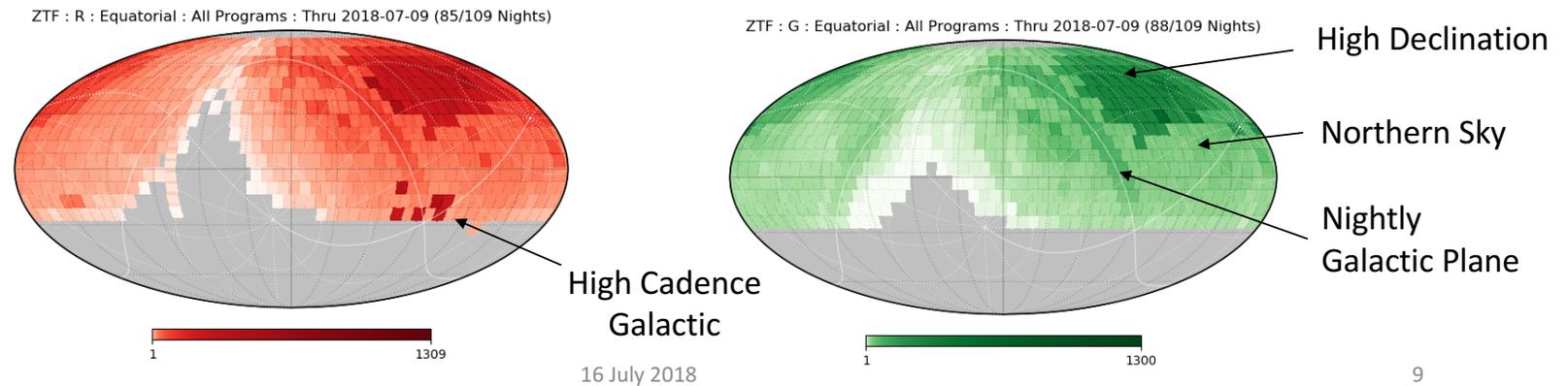
- Many possible end states depending on masses and constitution of WDs
- Binary components
  - He WD
  - C/O WD
  - O/Ne WD
  - Also sdB/sdO
- Merger end states
  - SN Ia
  - SN .Ia
  - R CrB
  - AIC (accretion induced collapse)
  - NS
  - C or O/Ne giant



# ZTF Survey Modes

ZTF Survey Mode	Time of Year	Total Area over 1 yr (deg <sup>2</sup> )	Visits (per field, per night)	Total Visits per year	Fraction of Total Time
→ Nightly Galactic Plane	April-Jan	3000	2 (g+R)	>150	6%
→ High-cadence Galactic	June-Aug + Nov-Dec	~1,250	~160 (g or R)	>300	~10%
→ Northern Sky	All-year	26,800	2 (g+R)	>150	34%
→ High Declination	Feb-Oct	3,300	6 (g+R)	>2000	22.5%

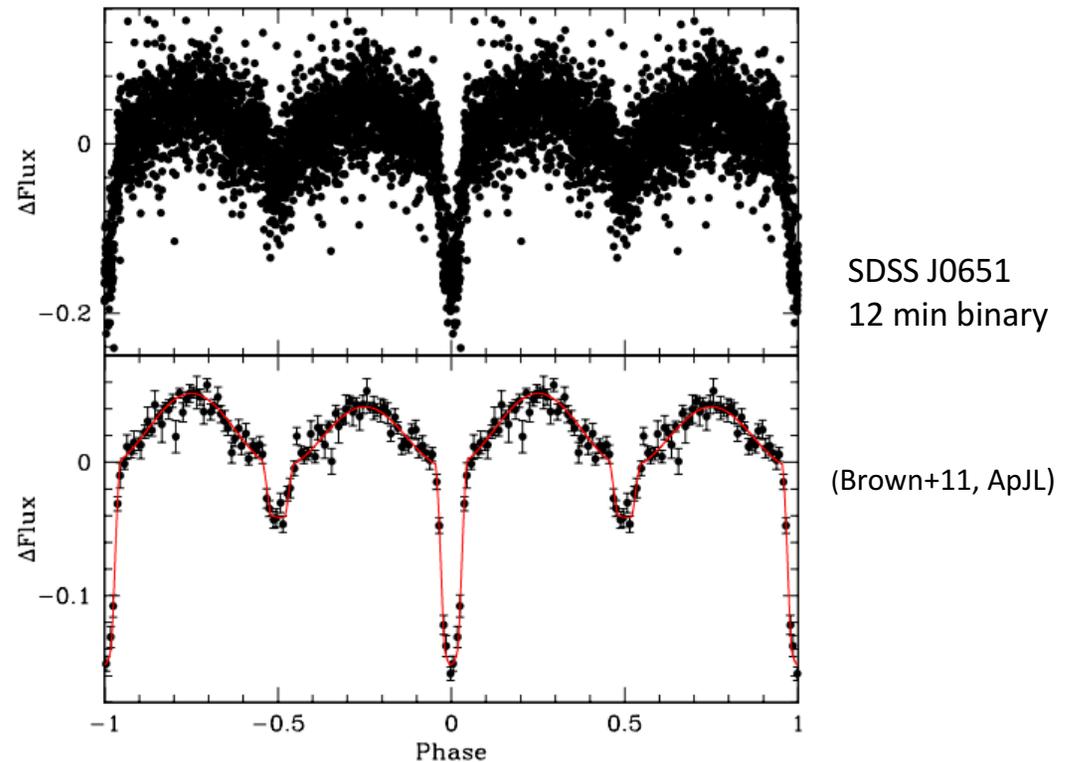
## Coverage as of 9 July 2018



# How do we find White Dwarf Binaries via periodicity?

- Eclipses
- Irradiation of companion (“reflection”)
- Ellipsoidal modulation

+ Searches over millions of objects using GPU-optimized periodicity search algorithms



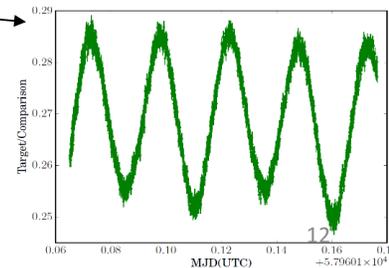
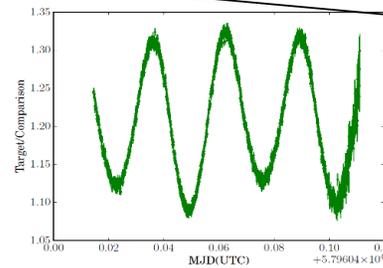
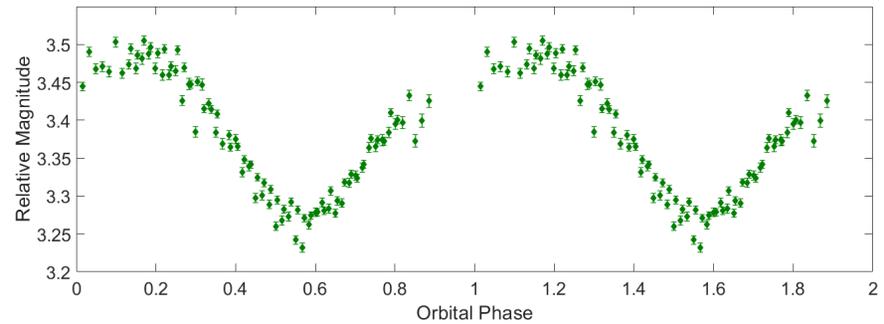
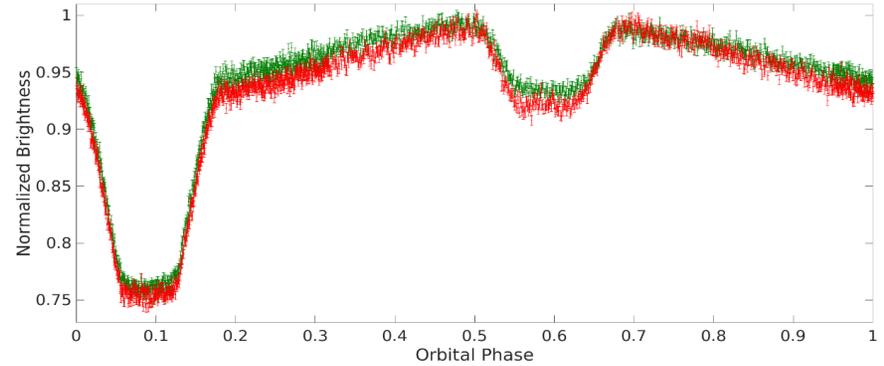
# New PTF and ZTF Results

## (Papers in preparation)

- Compact binary population paper (Burdge+18):
  - sdB/sdO and WD binaries
  - No details here, but very relevant to channels for formation of ultra-compact binaries such as LISA-detectable sources
- PTF-discovered sdB-WD binaries (Kupfer+18)
  - He detonation SNIa progenitors?
- PTF-discovered 20-minute DDWD binary (Burdge+18)
  - First LISA verification binary found solely via time domain periodicity search
  - Non-eclipsing. Periodicity due to ellipsoidal modulation
  - Follow-up high-speed photometry and spectroscopy
  - Decay of orbit due to gravitational radiation
- New ZTF 7-minute binary (Burdge+18)

# Population paper:

- Shortest Period HW Vir (sdB+MS) (P=92.4 min)
- Shortest Period Pre-CV (P=63.7 min)
- Three new WD-sdB Binaries (Kupfer et al in prep—see next)

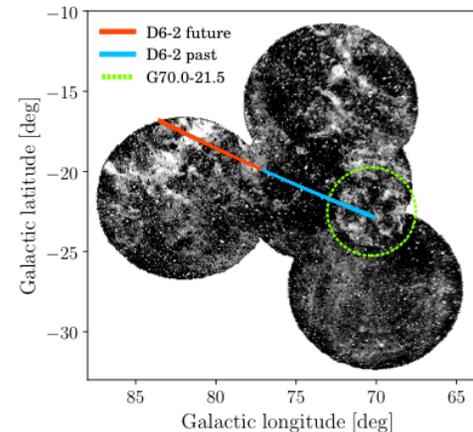
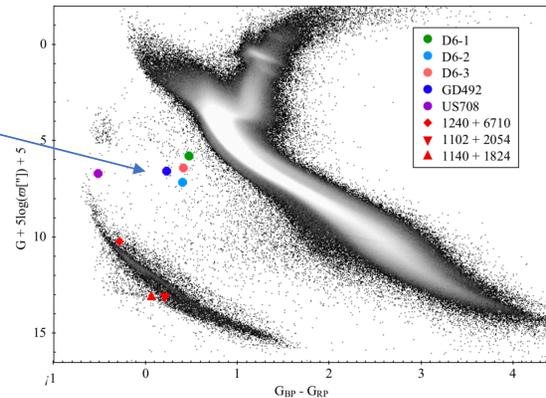


Topic #1:  
sdB-WD compact binaries as the  
progenitor systems of sub-  
Chandrasekar SNIa detonations

“The discovery of three new ultracompact hot subdwarf binaries”,  
Kupfer et al. (2018)

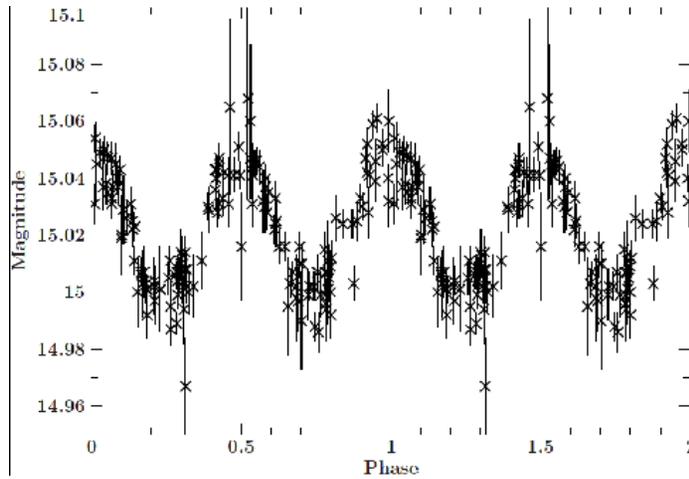
# Gaia discovery of 3 blue hypervelocity stars (Shen+18)

- “Three Hypervelocity White Dwarfs in Gaia DR2: Evidence for Dynamically Driven Double-Degenerate Double-Detonation Type Ia Supernovae”
- Favored explanation
  - Hypervelocity stars are blue companions of stars disrupted in SNIa explosion
    - Retain orbital velocity – appears as proper motion
    - One system points back toward SN remnant
  - What did the progenitor system look like?
    - Significant interest in sdB-WD binaries
    - Stripped He core: sdB/sdO (B-type sub-dwarf)
  - Formed from two CEEs
  - Evolve under GW emission
  - Come into contact
    - sdB donates He to WD
    - If massive enough, He-shell detonation which triggers detonation of C/O core



16 July 2018

## The first PTF discovered compact white dwarf + sdB

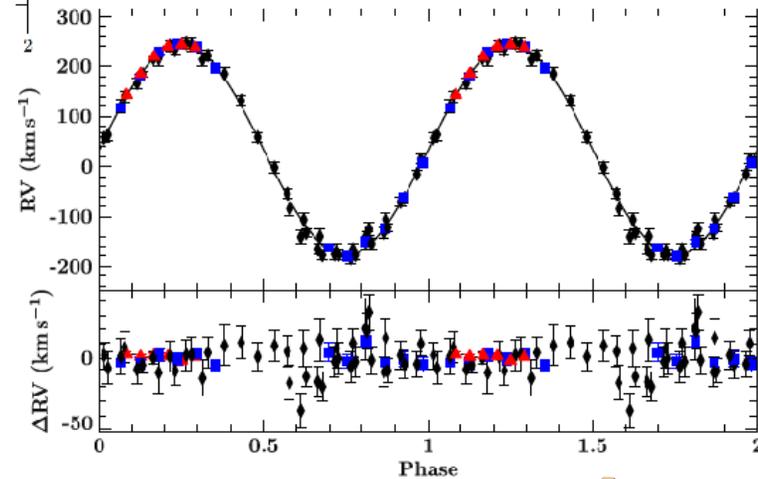


- PTF lightcurve shows 5% variability due to deformation of the He-star

$$M_{\text{sdB}} = 0.45 \pm 0.08 M_{\text{sol}};$$

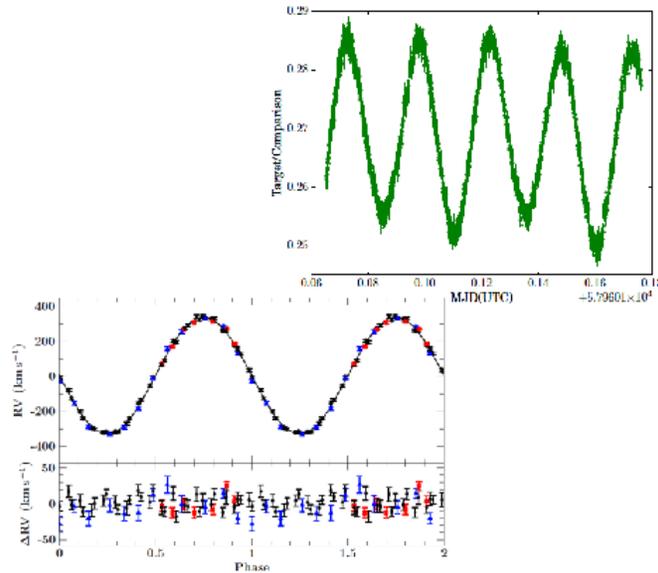
$$M_{\text{WD}} = 0.46 \pm 0.10 M_{\text{sol}}$$

PTFS1 J0823 - an sdB  
with a WD companion with  
 $P_{\text{orb}} = 87 \text{ min}$



...and there are even more...

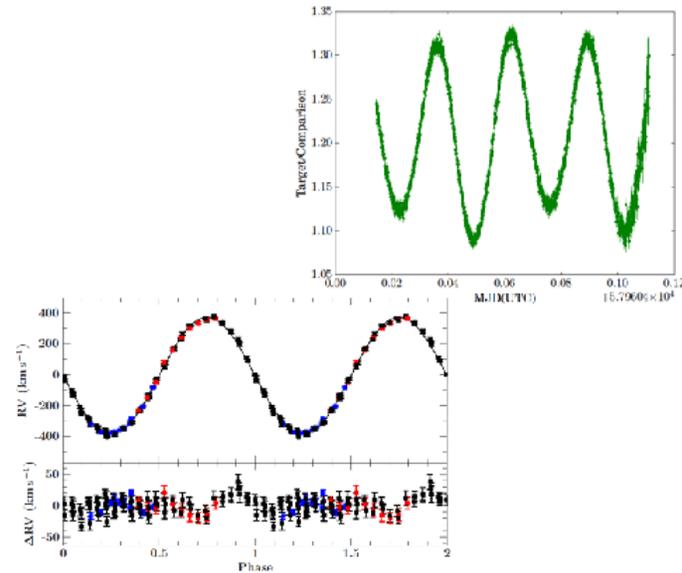
**PTFS1 J1821 (b=13.9deg)**



- **$P_{\text{orb}} = 72.1 \text{ min}$**
- $T_{\text{eff}} \sim 27\,000 \text{ K}$
- $\log(g) \sim 5.5$
- $v \text{rot} \sin(i) \sim 130 \text{ km/s}$
- $K \sim 333 \text{ km/s}$

minimum mass WD companion  $\sim 0.6 M_{\text{sol}}$

**PTFS1 J2238 (b=8.9deg)**

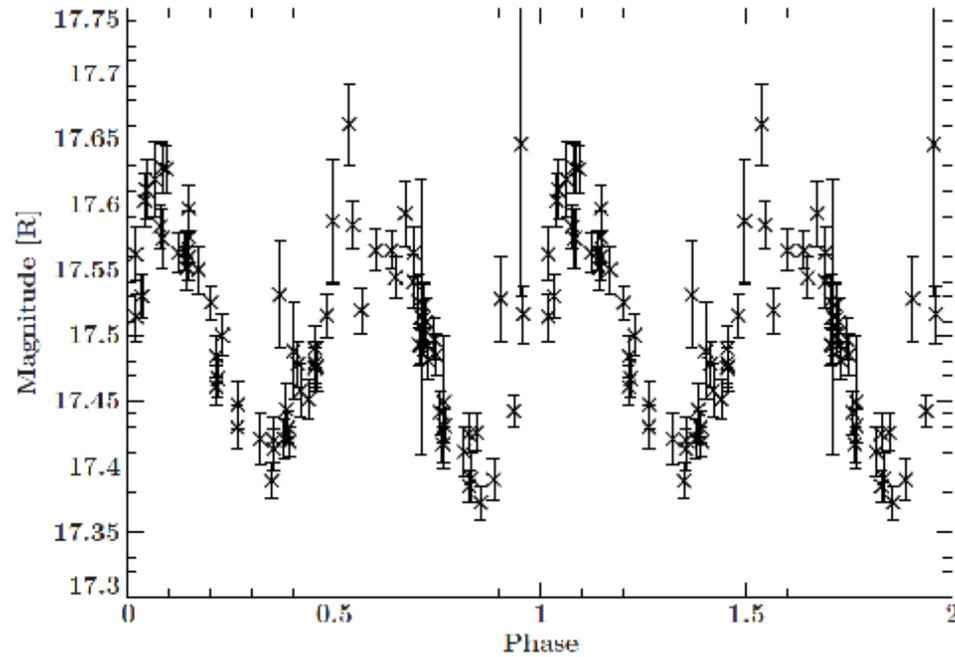


- **$P_{\text{orb}} = 76.3 \text{ min}$**
- $T_{\text{eff}} \sim 23\,000 \text{ K}$
- $\log(g) \sim 5.3$
- $v \text{rot} \sin(i) \sim 150 \text{ km/s}$
- $K \sim 378 \text{ km/s}$

minimum mass WD companion  $\sim 0.76 M_{\text{sol}}$

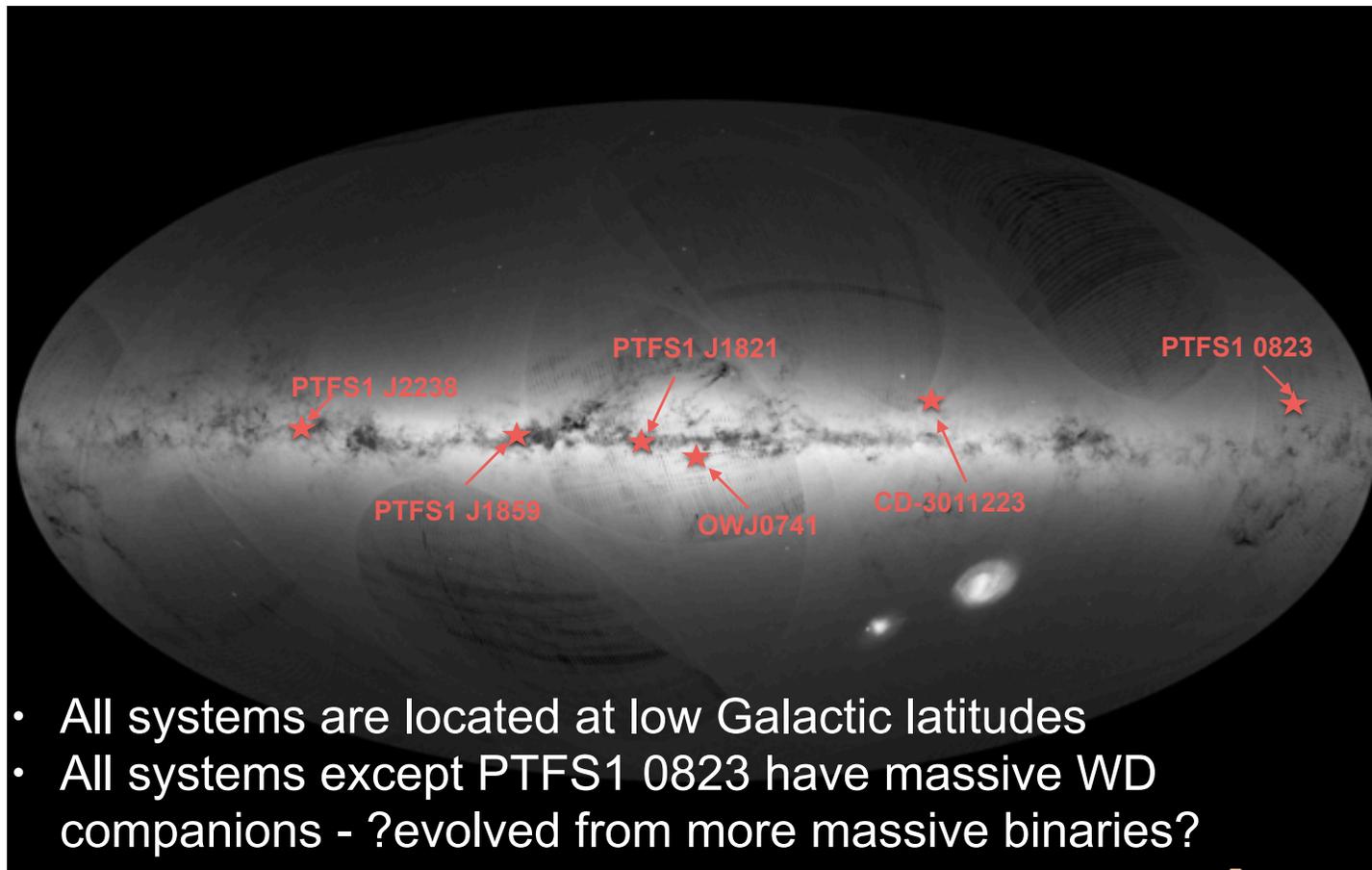
## PTFS1 J1859 (b=9.2deg)

... and more



- **$P_{\text{orb}} = 93.6 \text{ min}$**
- $T_{\text{eff}} \sim 25\,500 \text{ K}$
- $\log(g) \sim 5.5$
- $\Delta v > 450 \text{ km/s}$

## The sky location of the most compact hot subdwarfs



- All systems are located at low Galactic latitudes
- All systems except PTFS1 0823 have massive WD companions - ?evolved from more massive binaries?

## Galactic!

The ZTF High-cadence Galactic surveys will be excellent for discovering more of these sdB/O-WD systems

These are young (~100 Myr) massive stellar binaries

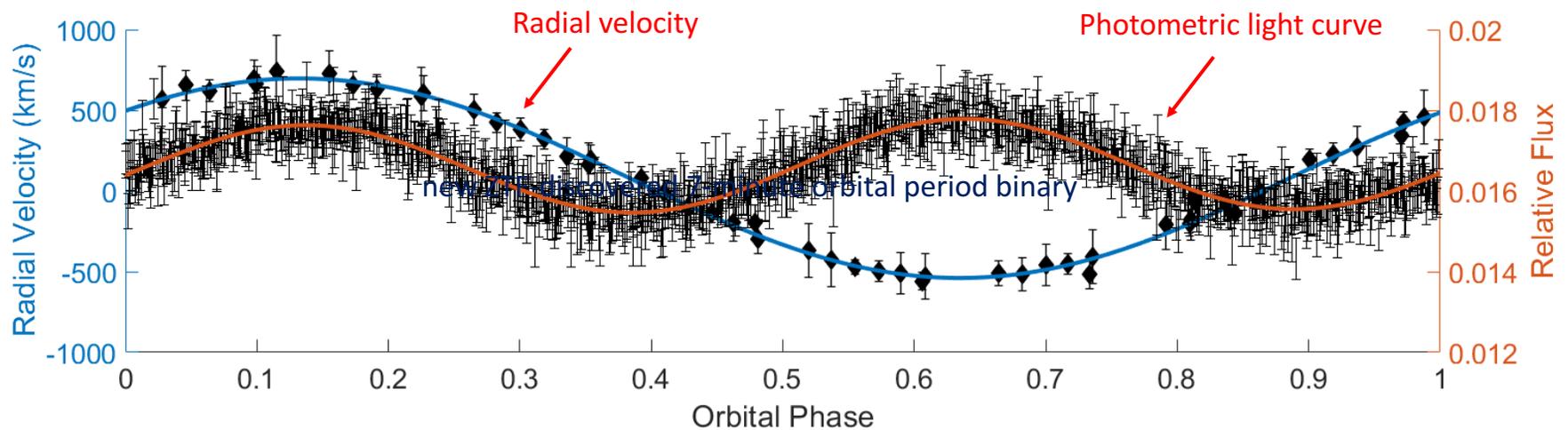
Bright – can be seen up to a few kpc

Topic #2:  
Ultra-compact WD-WD binaries  
(DDWDs) discovered through  
ellipsoidal modulations

“A 20 Minute Orbital Period Detached Binary with a Helium Extremely  
Low Mass White Dwarf”

Burdge et al. (2018)

# Keck and Palomar Chimera Observations of 20-minute Binary



Palomar Chimera g-band light curve  
Keck LRIS radial velocity curve

# A Helium Rich Extremely Low Mass WD

Some parameters from MCMC fit of lightcurve performed by Jan Van Roestel

$$M_1 \approx 0.09 M_{\text{sun}}$$

$$M_2 \approx 0.55 M_{\text{sun}}$$

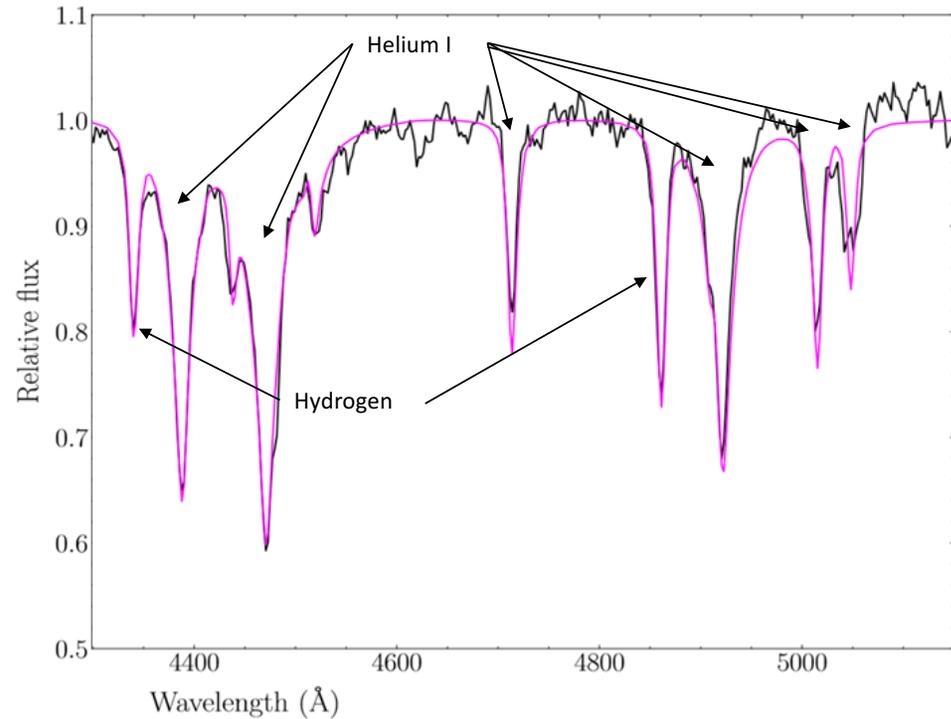
$$R_1 \approx 0.05 R_{\text{sun}}$$

Parameters from Atmospheric fit performed by Elena Cukanovaite, Pier-Emmanuel Tremblay

$$\log(g)_1 \approx 6$$

$$\log\left(\frac{N(H)}{N(He)}\right) \approx -2.8$$

$$T_1 \approx 18000 K$$



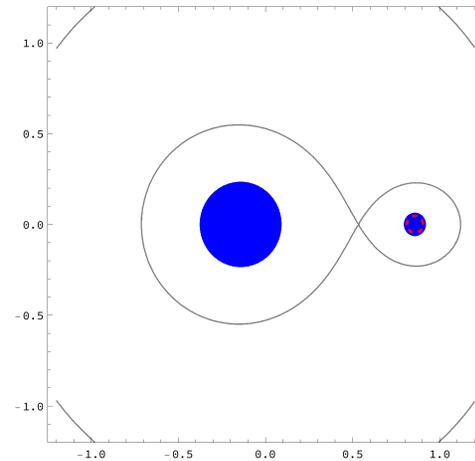
# Jan van Roestel Fit for 20-minute binary (22 July)

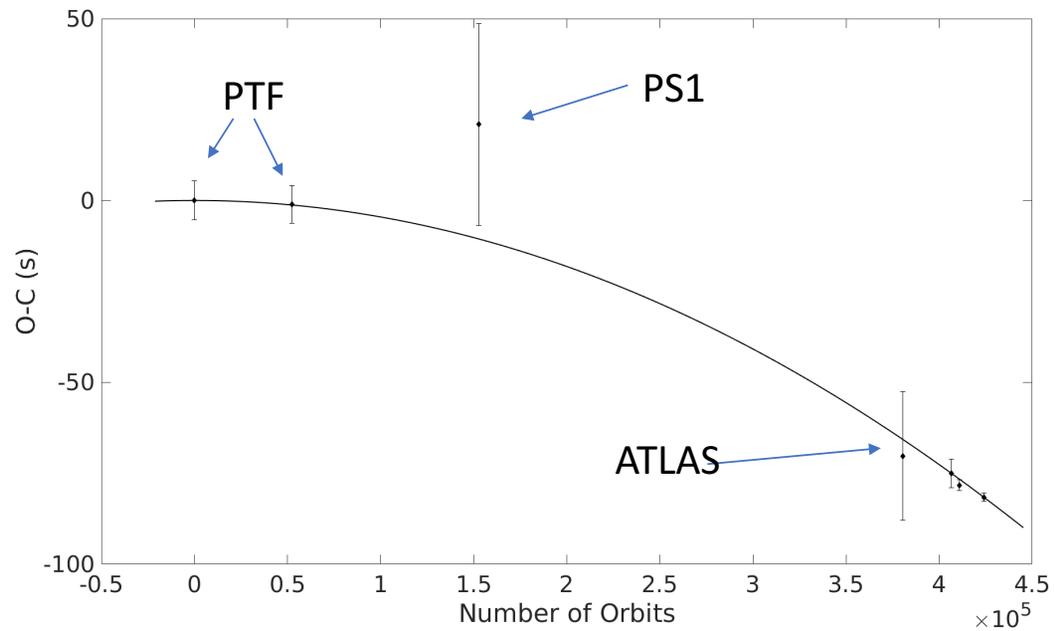
Probing the mass/radius/atmosphere  
of a very low-mass WD

→ M1 0.0929216553492 0.0108905736195  
M2 0.561282653981 0.0257311348856  
→ R1 0.0506929623265 0.00195965298662  
R2 0.0138369667604 0.000661979661836  
K1 623.199698368 7.48365900908  
K2 103.270744258 8.76175817823  
logg1 5.99626616833 0.0168872569504  
logg2 7.90194528114 0.0528461055283

Note  
small  
errors

Can calculate inclination from these => 72 deg





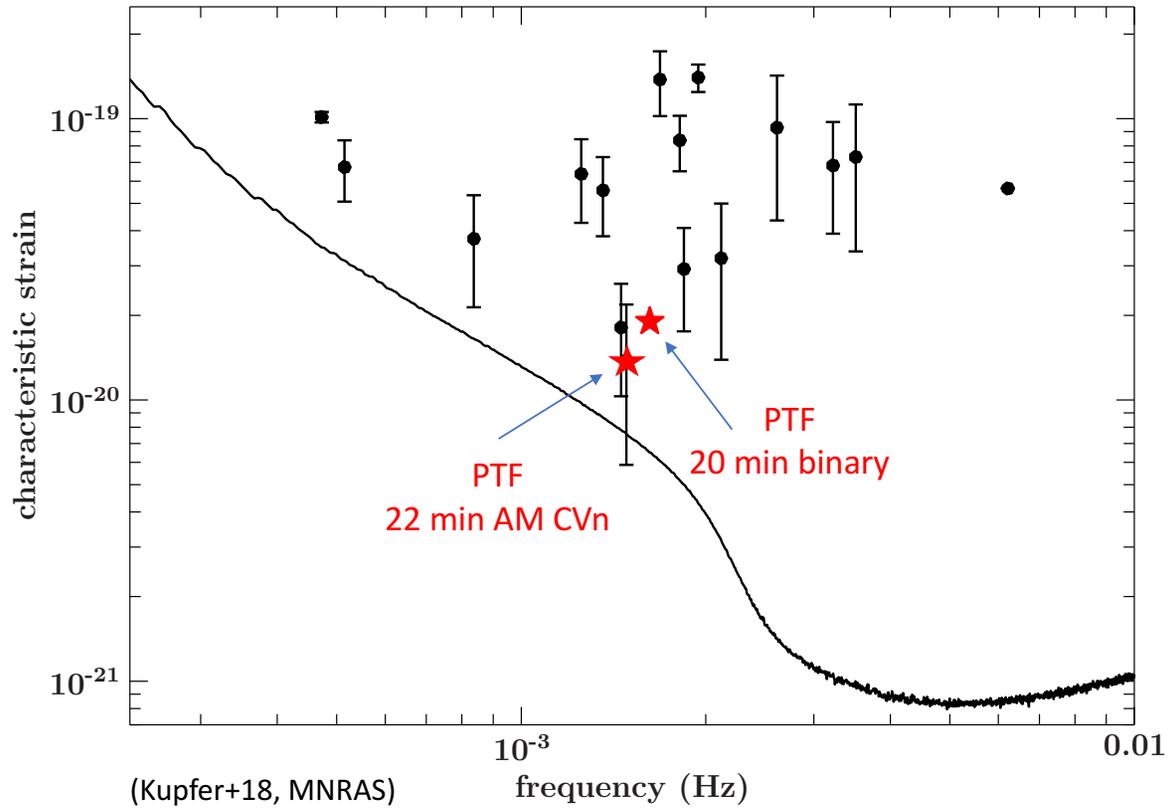
New observations coming later will pin down orbital decay

**Gravitational wave astrophysics w/o gravitational waves!**

**Figure 5.** This is an OC diagram constructed from the ephemeris derived from our PTF, Pan-STARRS, ATLAS, Chimera, and LRIS observations.

O-C = Observed - Computed

# LISA Verification Binaries



16 July 2018

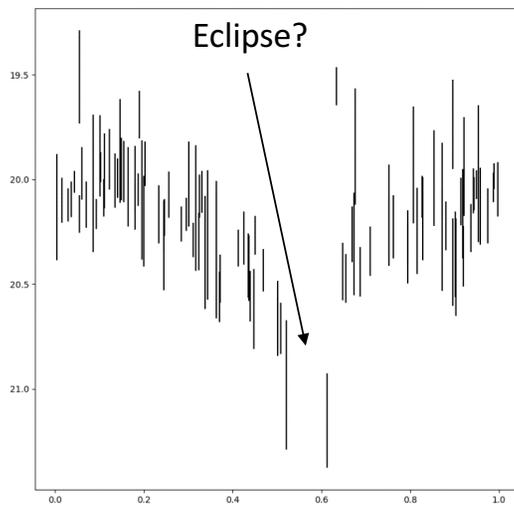
Topic #4:

New ZTF-discovered 7-minute  
orbital period binary

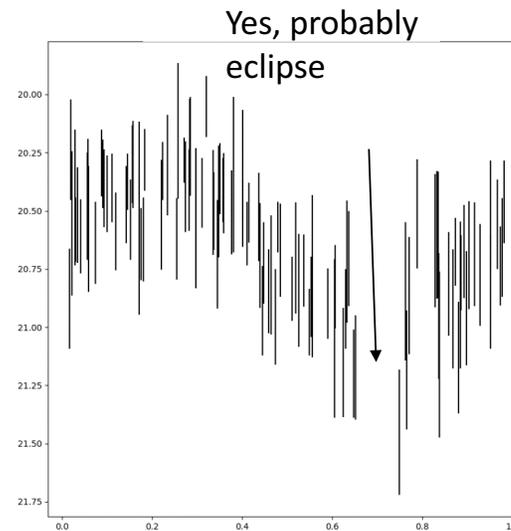
Burdge et al. (2018 – in preparation)

# ZTF Discovery Data

- Global period search of the *first* set of ZTF data
- And found an interesting candidate...

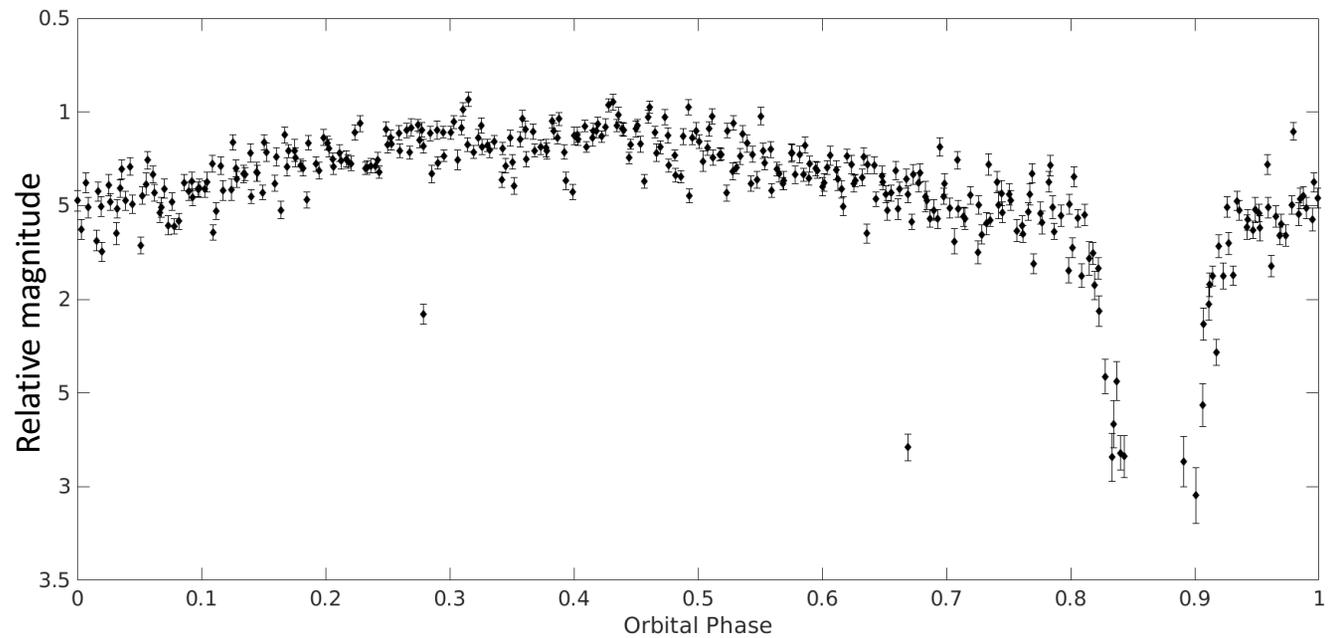


r-band



g-band

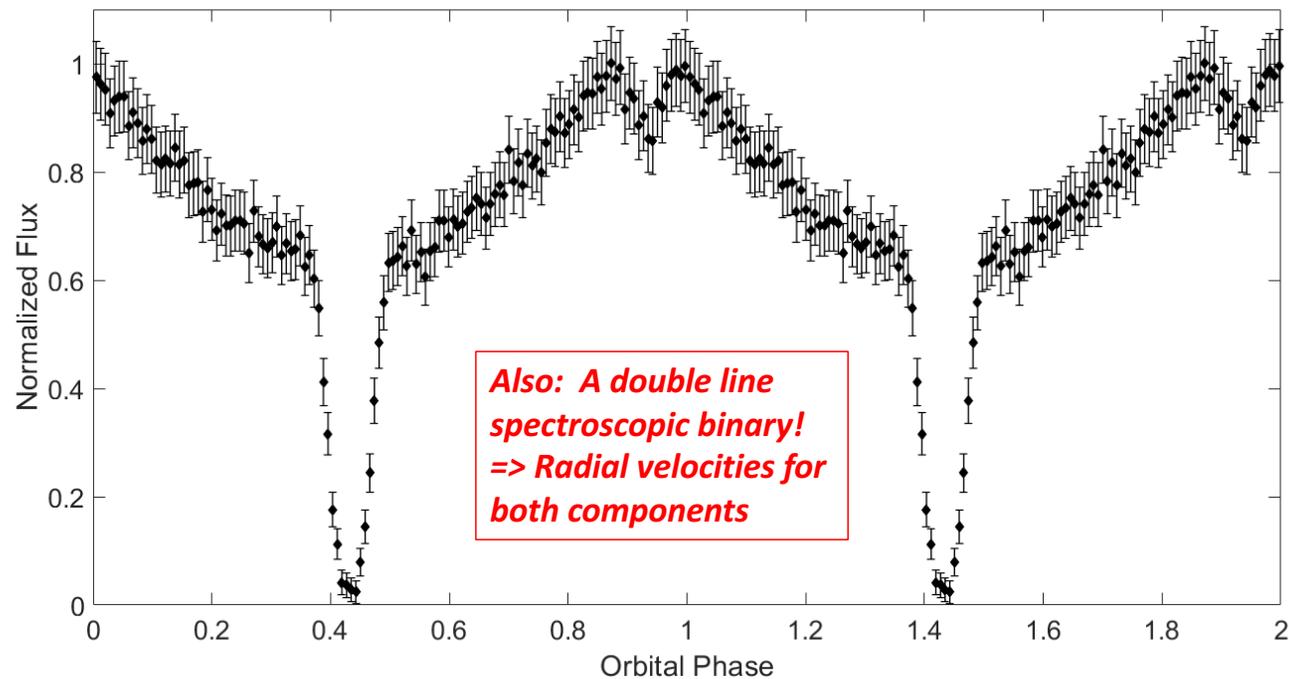
# Kitt Peak 84-inch EMCCD Photometer (First KP84 Light Curve of 7-minute Binary)



16 July 2018

# Recent Folded Light Curve for 7min Binary

## Palomar 200" Chimera High-speed Photometer

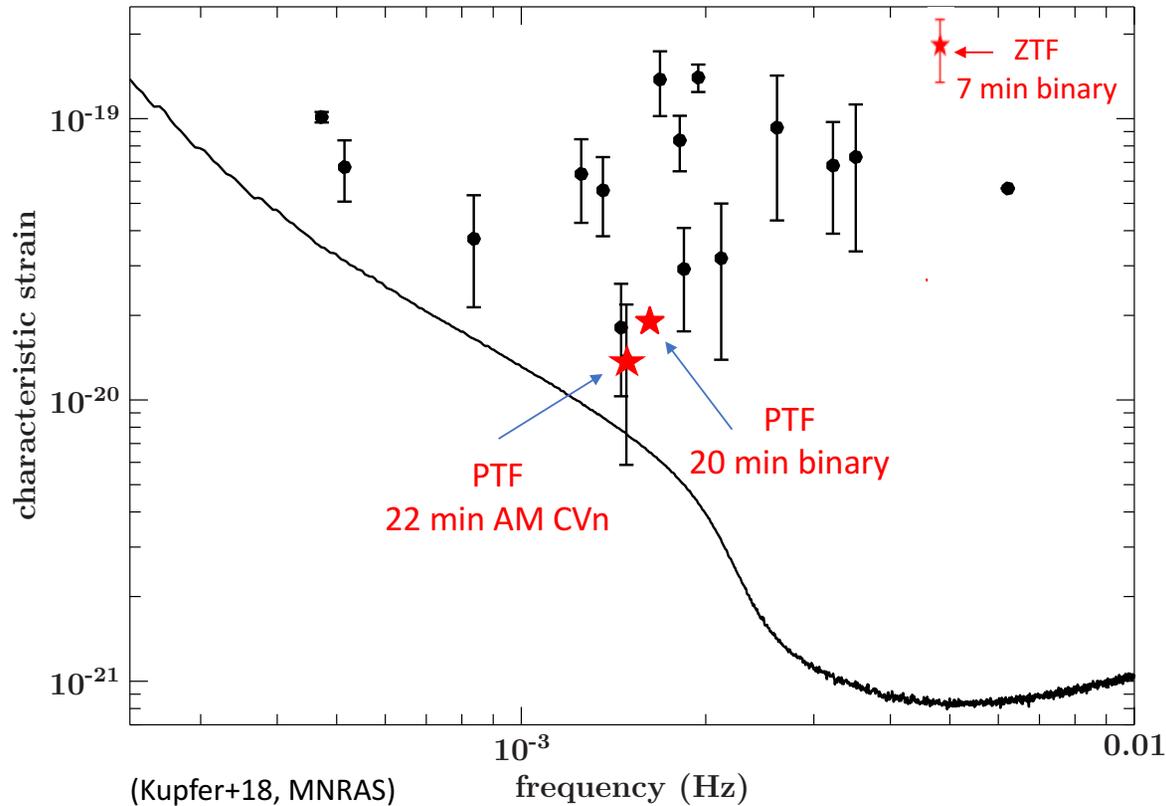


Primary and Secondary Eclipse  
+ Reflection  
+ Ellipsoidal

Excellent for timing evolution of orbital period, including GW and astrophysical processes (e.g. tides, or mass-transfer effects)

**Best short period binary ever for timing decay of orbit?**

## LISA Verification Binaries



## How many LISA verification binaries will ZTF find?

Korol+17 estimate that Gaia could discover  $\sim 250$  DWD systems via eclipses.

ZTF might be better than Gaia at close binary detection

- Better time sampling: 100's to 1000's of observations per field over 1 year vs  $\langle 70 \rangle$  for Gaia over 5 years.
- Sensitive to ellipsoidal and reflection effects, not just eclipses

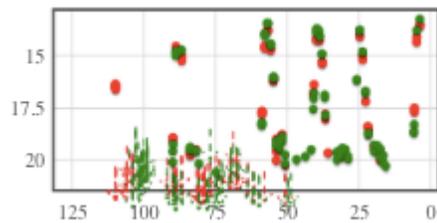
# Other stellar/variable topics:

- CVs
- M31/M33

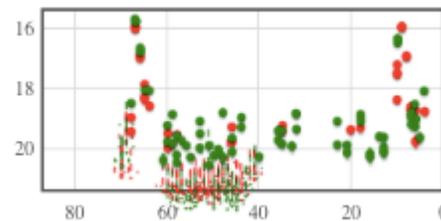
# Cataclysmic Variables from ZTF

Since April, > 25 known CVs (like AY Lyr below) and > 21 new CVs

Szkody + Kupfer



AY Lyr



New CV

# M31/M33 Observations

- M31
  - Nightly observations have recently started
  - 6 observations per night
- M33
  - Significant interest
  - Recent decision to do nightly observations of M33 using Caltech time
- M31/M33 Science Working Group
  - Will start up activity again in 2<sup>nd</sup> half of August
  - Soliciting interest from partnership members
- Currently: Dalcanton, Goobar, Graham, Hillenbrand, Kupfer, Ngeow, Prince, Szkody, Wilde (+ Drout, Soraisam?, also Bildsten)